Unsaturated Soils: Advances in Geo-Engineering – Toll et al. (eds)
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Testing for coefficient of permeability of a sandy soil in the residual state zone

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ABSTRACT: A series of evaporation tests were conducted in an environmentally controlled room in order to determine the unsaturated coefficient of permeability function for Beaver Creek sand in the residual state zone. Two boundary conditions were applied at the top of the evaporation column; namely, i) "radiation and wind" treatment, and ii) "wind" treatment. The results of the tests indicated that the "wind" treatment was more suitable method for the determination of the unsaturated coefficient of permeability function in the residual state zone. Further tests also revealed that the steady state conditions that appeared to be reached in a fairly short period of time (i.e. 3 to 4 days) might be an "apparent steady state" condition.

1 INTRODUCTION

An understanding of the permeability function for an unsaturated soil is required in modeling the unsaturated seepage problems. Estimation methods have often been used to determine the permeability function. Most of the available estimation methods show a continuous decrease in unsaturated coefficient of permeability, k_w, with increasing suction (or decreasing water content). A continuous decrease in the k_w with an increase in soil suction can cause numerical instability because of the high nonlinearity and the computing difficulties associated with extremely small numbers. More importantly, an unlimited decrease in the value of k_w fails to simulate actual water flow conditions since other moisture transfer mechanisms may cause moisture flow at relatively high soil suctions (Wilson et al. 1994, Gitirana Jr. & Fredlund 2003). Ebrahimi-Birang et al. (2004) suggested a lower limit of 10^{-14} m/s for k_w. Due to restrictions associated with experimental measurements, the unsaturated permeability behaviour of soils remains largely unknown in and beyond the residual state zone.

Amongst the methods that have been used for the measurement of the unsaturated coefficient of permeability, the evaporation method can be used to measure small coefficients of permeability in the residual state zone.

The primary objective of this research project was to measure the unsaturated coefficient of permeability in and beyond the residual state zone and also to investigate the mechanism of flow in a porous media when using an evaporation test. During the steady state evaporation method some interesting results were observed. The presentation and discussion of these results are the scope of the current paper.

2 BACKGROUND

The evaporation method to simultaneously measure the soil-water characteristic curve and permeability function was first introduced by Wind (1968). The method was a transient method and involved iterative calculations. Arya (2002) provided information regarding the modifications, commercial equipment, procedure and calculations associated with determining the unsaturated coefficient of permeability. The advantages and disadvantages of the method were also presented.

Mehta et al. (1994) used the steady state evaporation method to determine the unsaturated coefficient of permeability. Recently Fujimaki & Inoue (2003) applied the method with some modifications. The principle of the method is based on the assumption that the evaporation rate will start from the maximum rate (i.e. potential evaporation) when the soil column is saturated and will reduce with time and stay constant as the rate of the evaporation reaches the constant inflow rate which is applied from the bottom of the column. The inflow rate is always less than the potential evaporation rate. The test must be run in an environmentally-controlled room. In other words, the potential evaporation must be constant throughout the test. Equation 1 is used to calculate the coefficient of permeability. It must be noted that the soil-water characteristic curve must be measured separately. Research results have shown that steady state conditions appear to be reached within 2 to 3 days for a sandy soil.

$$k(\psi) = \frac{q - \frac{a\tau D_{va}\rho_v^*}{\rho_w R_v T}\exp\left(\frac{\psi}{R_v T}\right)\frac{\partial\psi}{\partial z}}{\frac{\partial\psi}{\partial z} - 1} \tag{1}$$

where $q = q_l + q_v, q_l$ and q_v = the liquid-water and water-vapour fluxes respectively, cm/s; z = depth, cm; a = the air-filled porosity, $\mathrm{cm}^3/\mathrm{cm}^3$; τ = the tortuosity factor; D_{va} = the diffusion coefficient of water vapour in free air, $\mathrm{g}/(\mathrm{cm}^2 \cdot \mathrm{s})$; ρ_{v^*} = saturated water vapour density; ρ_w = the density of water, $\mathrm{g/cm}^3$; R_v = gas constant for water vapour, 4697 cm/K; T = temperature, K; and ψ = soil suction.

3 EXPERIMENTAL PROGRAM

The soil-water characteristic curve for Beaver Creek Sand and details of the evaporation tests procedure are presented in the following sections.

3.1 *Soil used*

The Beaver Creek sand was used in this research study. The sand was air dried, passed through the sieve #10 (2 mm) and washed thoroughly in order to minimize the amount of salt. Then the properties of the soil were measured. Table 1 summarizes some of the properties of the Beaver Creek Sand. The soil will be referred to as "Sand" throughout the paper.

Table 1. Properties of Beaver Creek sand.

Soil properties	Beaver Creek sand
Sand	99.5 %
Silt and Clay	0.5 %
Specific gravity	2.65

3.2 *SWCC*

Hanging column method, Pressure plate (Tempe Cell and Fredlund Cell) and Chilled Mirror Dewpoint technique (WP4-T apparatus) were used to measure the soil-water characteristic curve of the sand for entire range of suction from zero to 1,000,000 kPa. The equation proposed by Fredlund & Xing (1994) was used to fit the experimental data. Figure 1 shows the experimental data and fitting SWCC for the sand. The air entry value for the sand was 1.7 kPa and residual suction state was reached at about 5 kPa.

3.3 *Evaporation test*

The soil column design, preparation of soil specimens and the evaporation test procedure are presented in the following sections.

3.3.1 *Soil column*

Figure 2 shows a schematic diagram of the soil column used in this study. The column is made of a Plexiglass tube with an inside diameter of 70 mm and a length of approximately 160 mm. Several holes were drilled along the column for the installation of the thermocouples. Eight thermocouples could be installed horizontally at different depths. These depths were: 4.5, 14.5, 24.5, 34.5, 49.5, 72, 112.5, and 147 mm. Some ports were also drilled around the perimeter of the tube to retrieve water content and electrical conductivity samples. The sampling ports in the top 40 mm of the column were smaller (5 mm in diameter) allowing sampling in closer proximity. There were three sampling ports for each depth in the top section of the column. The ports in the lower part of the column had a diameter of 10 mm. Soil samples could be taken from 16 different depths (i.e. 5.5, 10.3, 15.4, 20.5, 25.6, 30.7, 35.8, 40.9, 50.5, 60.4, 70.3, 80.5, 90.5, 100.5, 110.5, 120.5, 130.5, and 140.5 mm). The sampling ports were plugged using rubber stoppers during the test. A heat insulation jacket was used to prevent horizontal heat transfer in the upper part of the column. A porous plate with low air entry value was placed on a grooved pedestal. The column was attached to the pedestal using five bolts and nuts.

3.3.2 *Preparation of the soil sample*

The air-dried sand was mixed with a given amount of water to produce a gravimetric water content of 17%. The soil was left in a plastic container with a tight lid for a day. A Plexiglass tube with a diameter equal to that of the soil column was taped to the column to increase its height. The soil was placed into the column. In order to create a uniform soil, a vertical force was applied on top of the soil through a load cap. Extra soil was trimmed from top of the column. The column was slowly placed on the pedestal and fastened using the bolt and nuts. It should be noted that samples for the SWCC tests (section 3.2) were prepared using a similar procedure. However, the soil

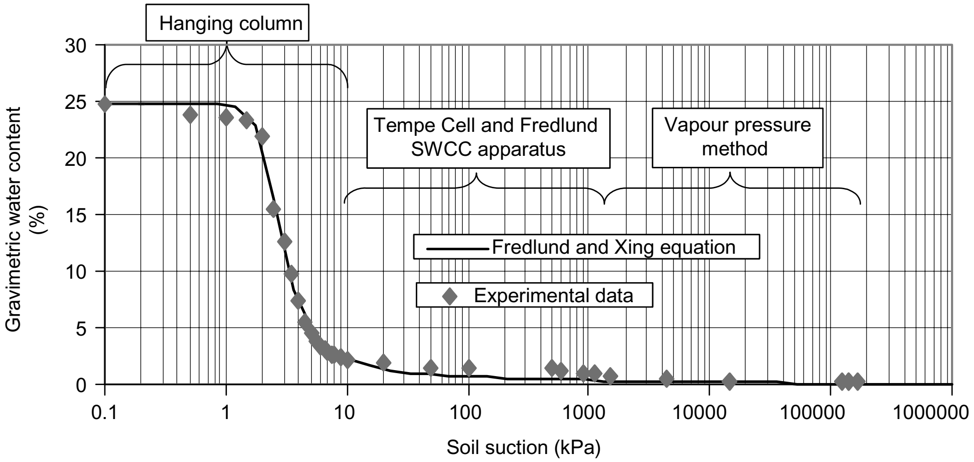


Figure 1. Soil-water characteristic curve of Beaver Creek sand.

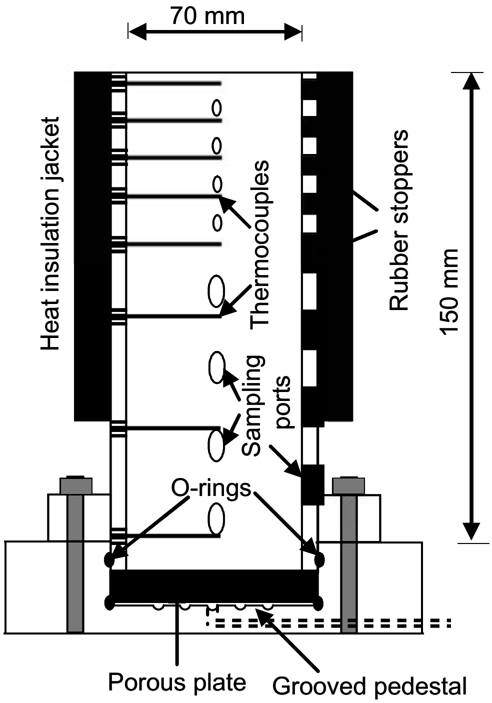


Figure 2. Schematic diagram of the soil column used in the evaporation test.

samples were extruded into stainless steel rings for the SWCC test.

3.3.3 *Test procedure*

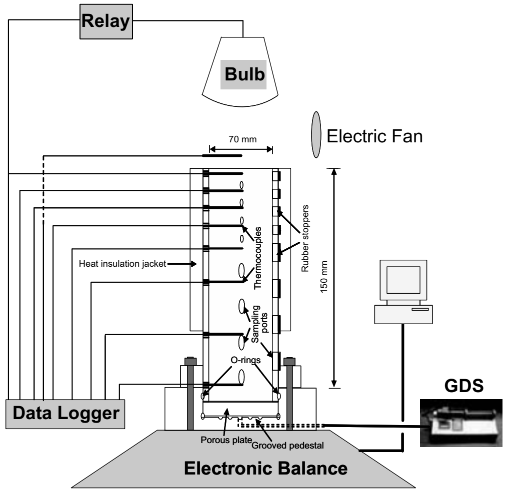


Figure 3. Schematic diagram of the evaporation tests.

The soil column was placed on an electronic balance (Fig. 3). Thermocouples were horizontally installed through rubber stoppers at specified depths along the column. The thermocouples were attached to a CR1000 Campbell Scientific data logger to monitor temperature during the test. The temperature of the ambient air above the soil column was also monitored using two thermocouples. The soil column was saturated by applying slow flow of distilled water from the bottom of the column. After saturation, the top of the soil was covered with a plastic sheet. The system was left overnight to reach equilibrium. A fiberglass tube was cut and placed around the top part of the column. Two pieces of Velcro were used to tighten the fiberglass around the column. A syringe pump (GDS apparatus) was attached to the column from the bottom through a plastic tube and a needle. The pump was programmed to apply a specified amount of distilled water into the column (0.36 cm^3/hr). The bottom porous plate had an air entry value of 1.8 kPa. The evaporation test was initiated by removing the plastic cover. An electric fan was used above the column to promote the evaporation. The weight of the soil column was recorded during the test using an electronic balance connected to a computer. The readability of the balance was 0.01 g.

The evaporation tests were conducted using two types of top boundary conditions; namely, i) "radiation and wind treatment" and ii) "wind" treatment. In the "radiation and wind treatment" an attempt was made to keep the temperature constant and equal to the room temperature along the soil column using a lamp and a relay.

All tests were conducted in an environmentally-controlled room. The room temperature was about 25.5°C and the relative humidity was about 26%. To minimize the effect of the radiation on evaporation, all lights were turned off during the test. The temperature and relative humidity in the room were also recorded using a hygrometer.

4 RESULTS AND DISCUSSIONS

4.1 *Weight of the column*

Figure 4 shows the change in the weight of the column during the evaporation test for the "wind and radiation" treatment. Steady-state conditions appear to have been reached after 3 to 4 days. A similar result was obtained for the case of the "wind" treatment. Further investigations have shown that this condition may not be a "true steady state" condition (see section 4.4). Further study is required with regard to "true steady state" conditions.

4.2 *Temperature profiles*

Figure 5 shows temperature profiles during early stages of the evaporation and after what appears to be "steady state" conditions. Temperature gradients are greater for the case of the "wind treatment". For the case of the "radiation and wind" treatment the temperature profile did not change substantially after "apparent steady state" conditions were reached. As can be seen in Figure 5a, the attempt to control temperature seems to be successful. The temperature gradients appear to be small. Further investigation is needed to determine the effect of temperature gradient on the flow through the soil.

4.3 *Water content profiles*

Water content profiles are shown in Figure 6 for both cases. For the case of the "radiation and wind" treatment it can be inferred that the coefficient of permeability cannot be determined for water contents below 5%. The corresponding suction for a water content of 5% is about 5 kPa (see Fig. 1). However, the water content profile for the "wind" treatment shows that it is possible to determine the corresponding coefficient of the permeability for water contents below 5%.

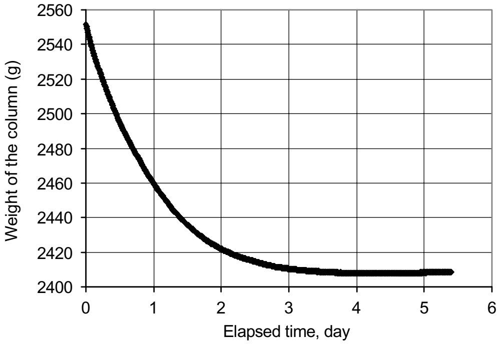
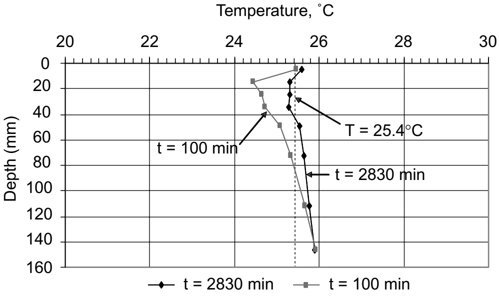
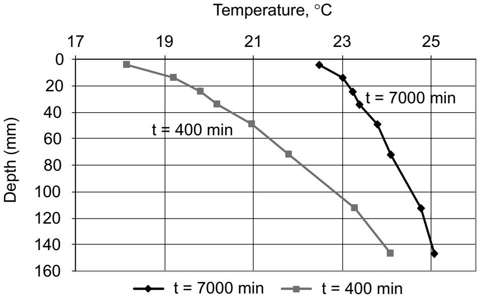


Figure 4. Change in the weight of the column for "wind and radiation" treatment.

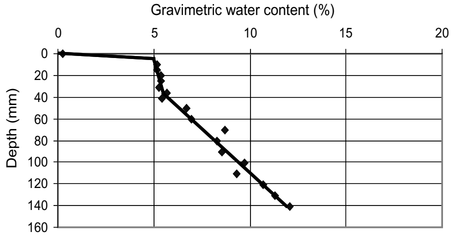


5a. "Radiation and wind" treatment

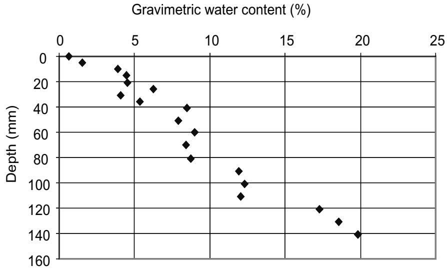


5b. "Wind" treatment

Figure 5. Temperature profiles for a) "radiation and wind" treatment, b) "wind" treatment.



6a. "Radiation and wind" treatment



6b. "Wind" treatment

Figure 6. Water content profiles for a) "radiation and wind" treatment b) "wind' treatment.

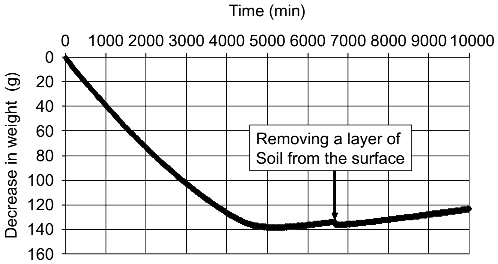


Figure 7. Weight of the column versus time for the "wind" treatment.

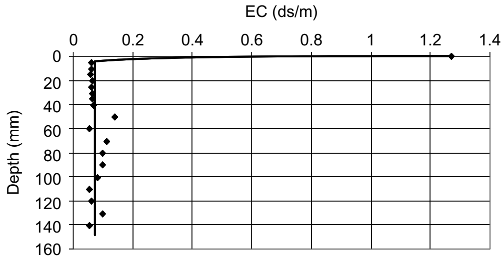


Figure 8. Electrical conductivity profile for the "radiation and wind" treatment (soil:water = 1:5).

4.4 *Steady state condition*

Equation 1 can be used along with the soil-water characteristic curve and the water content profile to calculate the coefficient of permeability provided a "true steady state" condition is reached.

Further tests must be conducted to determine if the observed steady state condition was truly a steady state condition. The evaporation test with the "wind" treatment was continued for a longer time after reaching an apparent steady state condition. The results of the change in the weight of the sand column are shown in Figure 7. After initiating the evaporation process, the weight of the column started to decrease. Then the weight remained constant for a couple of days (i.e. the steady state condition appeared to be reached). After a day or so the weight of the column started to increase indicating that the outflow rate (evaporation rate) was becoming less than the inflow rate. In other words the evaporation rate was still decreasing. There are two possible reasons for the increase of the weight: i) accumulation of the salts in the top layer of the soil and/or ii) break in the liquid-water continuity between the top and bottom of the column. These two reasons are discussed in the following sections.

4.4.1 *Salts accumulation*

Measurement of the salt profile after reaching the apparent steady state condition showed that the electrical conductivity, EC, of the soil in a thin layer of the soil surface was much higher than the EC for the bottom layers (Fig. 8). Electrical conductivity was measured for the samples with soil to water ratio of 1 to 5. It is possible that this may be related to the reason why the weight starts to increase. If so, then the "steady-state condition" should resume by removing a thin layer of the soil from top of the column. As can be seen in Figure 7 this did not happen and the weight of the column continued rising at the same rate.

4.4.2 *Break in the hydraulic continuity of liquid water*

To examine the hydraulic continuity of the liquid water throughout the soil column, a separate evaporation test was conducted. A soil column was prepared in a similar manner as before except that the porous plate with an air entry value of 100 kPa was used. The inflow rate was also increased to 0.9 cm^3/hr. After the apparent steady state condition passed and the weight of the column started to increase, the inflow rate was reduced to zero. As was expected a decrease in the weight of the column was observed after stopping the inflow rate as shown in Figure 9. The slope of the weight change line corresponds to a rate of evaporation of 0.0101 cm^3/min. The rate of evaporation did not change when compared with the rate before reducing the inflow rate to zero. This may be attributed to

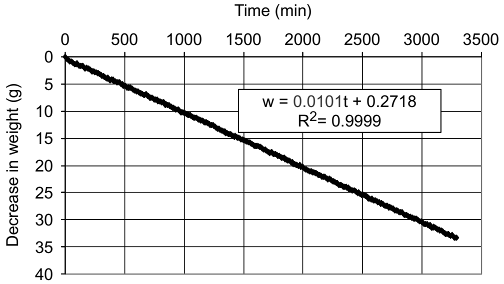


Figure 9. Decrease in the weight of the column (evaporation) versus time after reducing the inflow rate (inflow rate = 0).

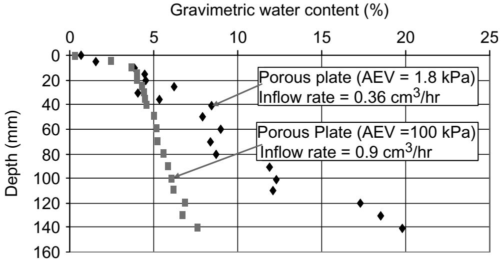


Figure 10. Water content profiles for two different conditions at the bottom of the column.

the fact that there was no hydraulic continuity of liquid water between the top and bottom of the soil column.

Plotting the water content profiles for the two different cases provides further evidence that it is possible that the liquid water was not hydraulically connected between the top and bottom parts of the column (Figure 10). The two cases created the same water content profile at the top of the soil while the bottom parts were different due to the change in inflow rate and the bottom plate. In other words, the top portion of the column was solely controlled by the ambient conditions.

5 SUMMARY AND CONCLUSIONS

A series of the evaporation tests were conducted on a sand column in an environmentally controlled room. The aim was to reach steady-state conditions during the evaporation tests and to determine the permeability function in the residual state zone. Two boundary condition treatments were tested, i) "radiation and wind" treatment, and ii) "wind" treatment. In the case of the "radiation and wind" treatment, an attempt was made to control the temperature of the soil column using a relay and lamp system. In both cases the evaporation was promoted with an electric fan above the soil column. While controlling of the temperature seemed to be successful, the water content profiles indicated that the "radiation and wind" treatment might not be a suitable method in order to measure the coefficient of permeability for the range of water content below 5%. On the other hand, the results for the "wind" treatment were encouraging.

Continuing the evaporation test for a long time showed that the "true steady state" condition may not have been reached during the short run of the evaporation tests. Two hypothesis were examined for the reason why the steady state condition may not have been attained; namely, i) accumulation of the salt in the surface of the soil and reducing the evaporation as a result, and ii) break in the hydraulic continuity of the liquid water between the bottom and top of the soil. Further investigation showed that the latter reason may provide the best explanation. Further tests are currently being conducting where the water table will be held constant within the soil column at a shallow depth. Hopefully, "hydraulic continuity" will be maintained between the top and bottom of the column.

REFERENCES

Arya, L.M. 2002. Wind and hot air methods. In J.H. Dane & G.C. Topp (eds), SSSA Book Series: 5, Methods of Soil Analysis, Part 4—Physical Methods: 916–926. Madison, Wisconsin: Soil Science Society of America Inc.

Ebrahimi-Birang, N., Gitirana, Jr. G.F.N., Fredlund, D.G., Fredlund, M.D. & Samarasekera, L. 2004. A lower limit for the water permeability coefficient. Proceedings of the 57th Canadian Geotechnical Conference: 12–19, 24–27 October 2004. Quebec city, Canada.

Fredlund, D.G. & Xing, A. 1994. Equations for the soil water characteristic curve. Canadian Geotechnical Journal 31(3): 521–532.

Fujimaki, H. & Inoue, M. 2003. A flux-controlled steady-state evaporation method for determining unsaturated hydraulic conductivity at low matric pressure head values. Soil Science 168(6): 385–395.

Gitirana, Jr., G.F.N. & Fredlund, D.G. 2003. From experimental evidences towards the assessment of weather-related railway embankment hazards. Keynote address, Proc. of the International Conference on "From Experimental Evidences Towards Unsaturated Soil Practice", Sept. 18–19 Weimar, Germany.

Mehta, B.K., Shiozawa, S. & Nakano, M. 1994. Hydraulic properties of a sandy soil at low water contents. Soil Science 157(4): 208–214.

Wilson, G.W., Fredlund, D.G. & Barbour, S.L. 1994. Coupled soil-atmosphere modeling for soil evaporation. Canadian Geotechnical Journal 31(2): 151–161.

Wind, G.P. 1968. Capillary conductivity data estimated by a simple method. In P.E. Rijtema & H. Wassink (eds), Proc. Wageningen Symp. on Water in the Unsaturated Zone, Paris, June 1966, Vol. 1: 181–191 Int. Assoc. of Scientific Hydrol., Gent/Brugge/UNESCO.